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Freezeup Dynamics of a Frazil Ice Screen

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PREFACE

This report was prepared by Kathleen D. Axelson, Research Hydraulic Engineer, Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this work was provided by CWIS 31792, *Frazil Ice Control for Field Use.*

The report was technically reviewed by Dr. George D. Ashton and Steven F. Daly (both of CRREL). The author is grateful to Brian Bennett and David L. Marcotte III for performing the first test series. The author is also grateful to Steven F. Daly for his assistance. The author was assisted by John Gagnon in conducting experiments in the hydraulic flume, Edward Perkins and Matthew Pacillo in drafting the final figures, and Pamela Bosworth in word processing.

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Freezeup Dynamics of a Frazil Ice Screen

KATHLEEN D. AXELSON

INTRODUCTION

In many northern rivers, frazil ice blocks water intakes and forms ice jams that are a hazard to winter navigation and often result in flooding. To study ways to control frazil ice, we generally address the formation or transport of frazil ice. Large heat losses from the water surface are required to produce frazil ice. Because an ice cover insulates, thus reducing heat loss, formation is suppressed when river reaches where frazil ice is produced become ice covered. Also, the amount of frazil transported may be reduced by accumulation at the upstream edge of the ice cover or as deposits beneath the ice cover.

Fence booms made of wire mesh screen, which incorporate frazil ice when it freezes to the screens, have been proposed as economical, temporary control structures to raise the water level at a specific location. This will promote the formation of an ice cover (Fig. 1), thus decreasing both frazil ice production in the vicinity of the structure and transport from upstream reaches (Perham 1986, Foltyn 1986, Zufelt 1987). However, every time a fence boom has been used, bed scour beneath the structure has been observed, which reduces the effectiveness of the structure as a control.

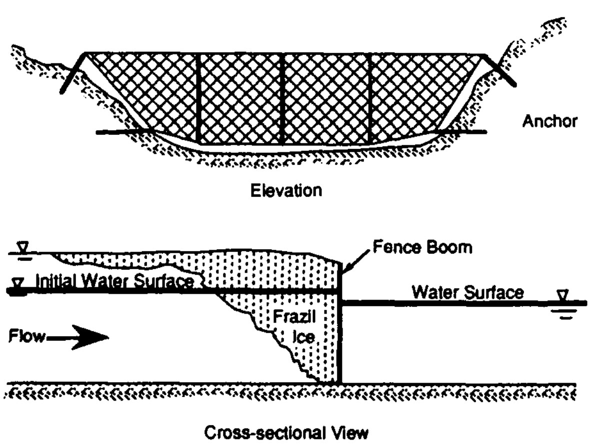


Figure 1. Schematic of fence boom. The cross-sectional view shows the fence boom once a frazil ice dam has been established.

To predict the scour potential, the freezeup and blocking mechanisms of the wire mesh screens and the resulting velocities must be characterized. This report describes experiments designed to qualitatively examine the freezeup of a fence boom made of expanded metal screen and to measure the velocity profiles associated with various stages of freezeup. In one set of experiments, we examined freezeup by artificially blocking an expanded metal screen. In the second set of experiments, we examined the behavior of an expanded metal screen that was partially and completely blocked by frazil ice.

Four stages of frazil blockage were identified in the experiments. In the first stage the screen is progressively blocked by frazil ice from the top downwards, and velocity jets form downstream from the structure. In this stage the flow is similar to orifice flow. The second phase is the transition stage, in which blocking progresses and flow is a combination of orifice flow beneath the frazil deposit and flow through the porous frazil deposit. The third stage, the permeable flow stage, occurs when the screen is completely blocked and flow through the porous frazil deposit dominates. The fourth phase, that of weir flow over the screen, occurs as the frazil ice solidifies. The results should be helpful in locating sites where screen-type fence booms would be effective and in estimating scour protection needs.

EXPERIMENTAL METHODS

The first set of experiments were conducted in an unrefrigerated hydraulic flume, which is described in detail by Calkins (1974). The frazil screen, made of commercially available expanded metal, covered the full depth (0.9 m) and width (0.9 m) of the flume at the midpoint. The large dimension of the screen's diamond-shaped openings measured 5.8 cm and the short dimension was 2.3 cm. Plywood sheets, 1.14 cm thick, were used to block the expanded metal screen. Tests were run with the metal screen blocked from the top at 10, 25, 50 and 75% of its depth; top blocking has been observed in the field. Velocity profiles were measured at the centerline of the flume using a Marsh-McBirney magnetic current meter at 61, 30.5 and 15.2 cm upstream from the expanded metal screen and 15.2, 30.5, 61 and 91.5 cm

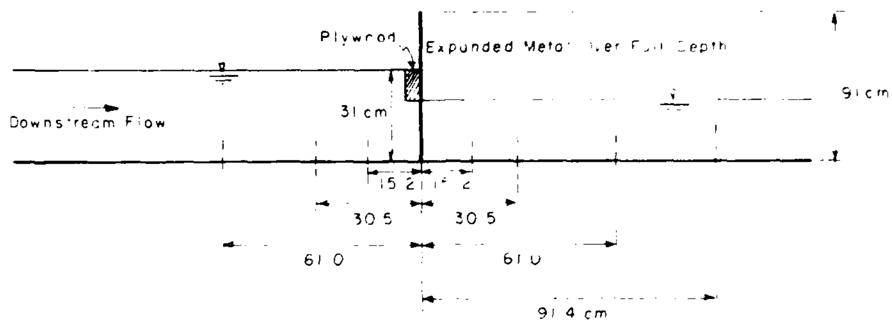


Figure 2. Experimental setup for partial impermeable blocking of expanded metal screen.

Table 1. Flume experiments

Test no.	*Screen height*	*Flow (m^3/s)*	*Screen placement*	*Air temperature (°C)*	*Seeder*	*Length of test (min)*	*Reason ended*
WO	None	0.07	None	20		—	Uniform flow achieved
WS	Full	0.07	—	20		—	Uniform flow achieved
WS10	Full 10% blocked	0.07	—	20		—	Uniform flow achieved
WS25	Full 25% blocked	0.07	—	20		—	Uniform flow achieved
WS50	Full 50% blocked	0.07	—	20		—	Uniform flow achieved
WS75	Full 75% blocked	0.07	—	20		—	Uniform flow achieved
RF1	Full	0.019	Before supercooling	−15	X	57	Structure failure
RF2	Full	0.019	After supercooling	−15	X	70	Equipment maintenance
RF3	Full	0.019	After supercooling	−15	X	65	Head > 20 cm
RF4	Full	0.019	After supercooling	−15	X	64	Structure failure
RF5	Full	0.019	After supercooling	−15	X	50	Structure failure
RF6	Full	0.019	After supercooling	−15		108	Head > 20 cm, stable ice sheet
RF7	Full	0.013	After supercooling	−15	X	132	Head > 20 cm, stable ice sheet
RF8	Full	0.013	After supercooling	−10	X	196	Head > 20 cm, stable ice sheet
RF9	Full	0.013	After supercooling	−17	X	226	Head > 20 cm, stable ice sheet
RW1	15 cm	0.019	After supercooling	−15	X	70	Head > 20 cm
RW2	15 cm	0.019	Before supercooling	−15		170	Head > 20 cm
RW3	15 cm	0.013	After supercooling	−15	X	217	Head > 20 cm, stable ice sheet

downstream (Fig. 2). The upstream water depth at the start of the test was about 31 cm and the average upstream velocity was about 22 cm/s.

The second set of laboratory experiments was carried out in the CRREL refrigerated hydraulic flume facility, using frazil ice produced in the flume. The flume, described in detail by Daly et al. (1985), is 36 m long, 1.2 m wide and 0.6 m deep. For all the tests, the slope of the flume was adjusted to 0.00528 m/m, flow rate was either 0.01 or 0.02 m^3/s, and the room air temperature was about −15°C. The initial depth of water in the flume prior to placement of the test structure was about 12.4 cm. The test material consisted of a commercially available expanded metal screen with diamond-shaped openings that were 3.8 cm wide and 2 cm high. The screen was placed at the midpoint of the flume. For nine tests, a full-depth screen was used, and for three tests, a 15-cm-high screen was used.

Water temperatures were measured using individually calibrated glass bead thermistors attached to a 10-channel digital thermometer recorder (Trachier 1987), which applies the Steinhart–Hart equation to the resistance of the thermistor. This system has an accuracy of ±0.01°C. Water temperatures were also measured using a single glass bead thermistor connected to a Fluke 8060A digital multimeter, with an accuracy of ± 0.02°C around the freezing point of water.

Velocity profiles were measured about 20 cm downstream from the structure at the approximate centerline of the flume with a Marsh-McBirney current meter and recorded by the satellite data acquisition system (Zabilansky 1988). During two tests, we also measured velocity profiles at the center of the flume about 70 cm upstream from the structure by directly reading a Marsh-McBirney current meter.

For each test run, the room was cooled to −15°C and water temperatures were monitored. For two tests, the expanded metal screen test structure was placed in the flume prior to cooling of the room. For the other tests, the structure was placed in the flume after supercooling of the water was measured. Supercooling was observed throughout the measuring periods. Water temperature and headwater and tailwater elevations were recorded at approximately 5-minute intervals. Ice growth on the test structure was monitored by an overhead color video camera and an underwater color video camera that was located at the centerline of the flume about 1.5 m upstream from the test structure. Tests were terminated in three cases after the test structure moved. The other tests were terminated after a head difference across the screen greater than 20 cm was achieved. One test was halted prematurely for equipment maintenance. The experiments are summarized in Table 1.

Frazil ice crystals and flocs were observed throughout the water column during the entirety of each test. Of the four major factors in frazil ice production—seeding rate per unit volume, heat loss rate, turbulent energy dissipation rate and the number of crystals produced per unit of collision energy (Mercier 1984)—only the first three can be controlled to any degree during the experiment. The heat loss rate is controlled largely by room temperature, and the turbulent energy dissipation rate by the slope, roughness and discharge through the flume, all of which were reasonably constant during these experiments. The background seeding rate provided by the room refrigeration system can be increased by using a seeder, which sprayed a fine mist into the air above the flume head box. This mist would freeze and greatly increase the number of seed crystals available. The seeder was used in all but two tests.

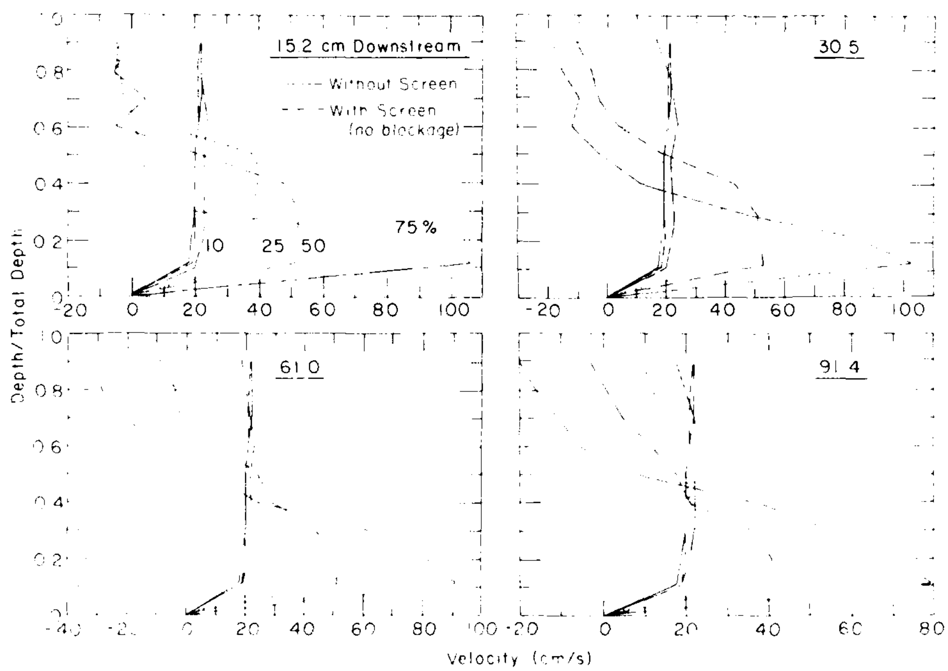
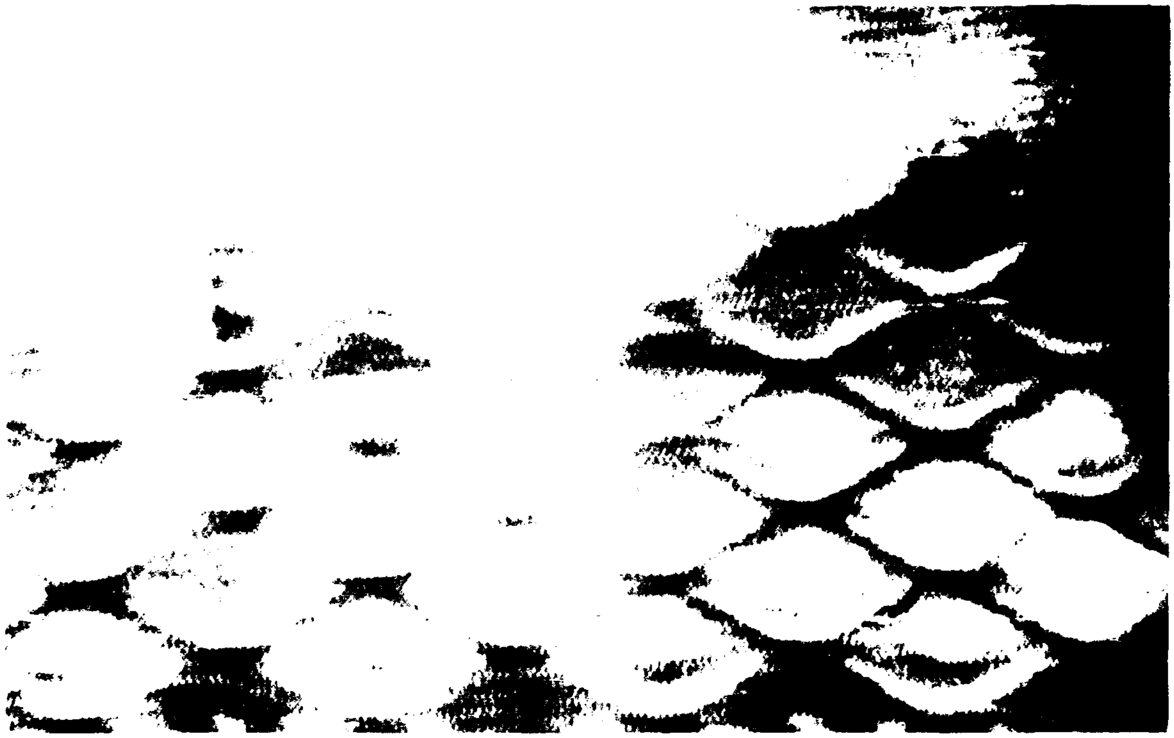


Figure 3. Velocity profiles measured at the centerline of the flume downstream from an expanded metal screen with varying degrees of partial impermeable blocking.



a. Early stage.

b. Late stage.

Figure 4. Two stages of frazil blockage of expanded metal screen.

RESULTS

Frazil blockage simulated by use of an impermeable barrier

The first set of tests simulated partial impermeable blocking of the test structure. For the different blocking schemes, the velocity profiles at the centerline of the flume at various distances downstream from the test structure are shown in Figure 3. There is a dramatic increase (five-fold) in the velocity near the channel bed as the expanded metal was progressively blocked from the surface downwards. The formation of regions of high velocity under these conditions seems likely. The maximum measured velocities were located at a distance downstream approximately equal to the upstream water level. All flow through the blocked structure was pressure (orifice) flow except in the test where 75% of the screen was blocked; here, weir flow over the plywood was noted.

Frazil blockage

The second set of tests illustrates the partial and complete blocking of an expanded metal screen by frazil ice, which may be considered a porous medium (according to Ashton [1983], the porosity of frazil deposited beneath an ice cover typically ranges from 0.4 to 0.7). For all tests, we noted adherence of frazil ice to the structure just after we first observed supercooling of the water. Freezeup and blocking of the structure occurred by frazil ice adhesion, crystal growth and deposition. Deposition, the primary mechanism of blocking, proceeded from the water surface downwards. Frazil particles adhered to the metal over the full depth of the screen. This coating of ice increased by thermal ice growth and by accretion of frazil particles suspended in the water column (Fig. 4). A large portion of the growth of the frazil ice mass occurred when frazil flocs transported at the water surface were deposited at the edge of the ice cover, where we observed underturning and shoving of the flocs. An ice sheet up to 20 m long was formed upstream from both the full-height screen and the weir-height screen. Frazil continued to deposit and grow until the screen was fully blocked (Fig. 5). The underwater video camera recorded complete blocking of the structures in all tests.

A series of downstream velocity profiles and the maximum downstream velocities measured at the centerline of the flume are shown for test RF6 (Fig. 6). In this test, the flow was concentrated through the lower portion of the structure as the upper portion of the test structure became blocked with frazil. Eventually, a region of high velocity (a jet) formed through the lower, unblocked portion of the structure; this was similar to what happened in the first set of tests. In other tests with frazil ice, freezeup and blocking of the test structure occurred so rapidly that a jet had formed before the first profile was measured. Typically, the maximum velocity of the jet was more than three times the maximum velocity of the profile obtained shortly after placement of the test structure.

During the later part of the frazil ice dam formation, the maximum velocity decreased. Flow through the entire height of the frazil ice dam was visible. Weir flow was noted at times, as were areas of concentrated flow through the structure, perhaps attributable to piping through the porous mass. In some tests, the downstream velocity profile returned to a shape near its initial profile by the end of the test. The profiles at the longest time indicate that flow may be a combination of flow over and through the porous frazil ice dam.

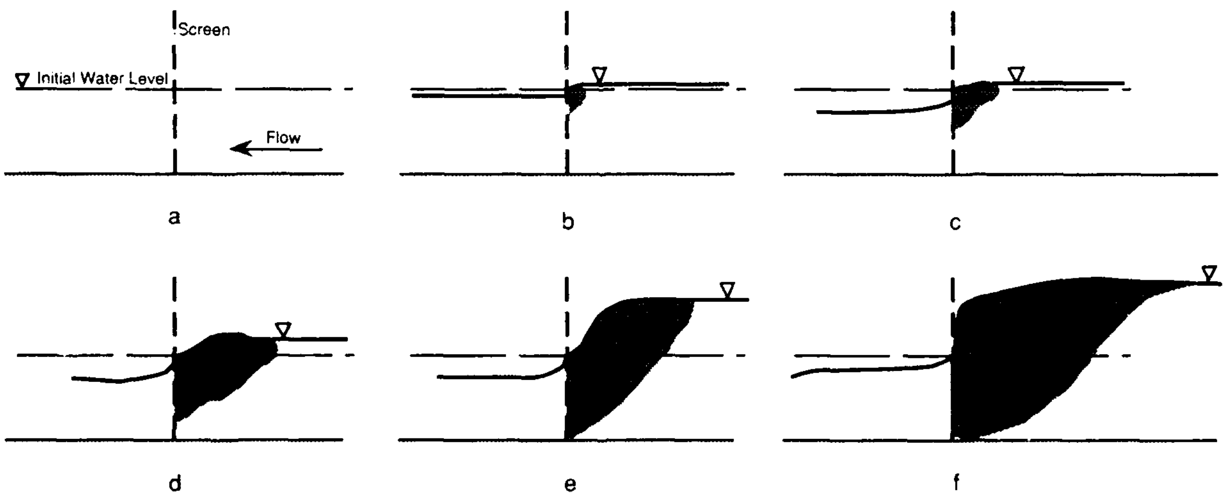
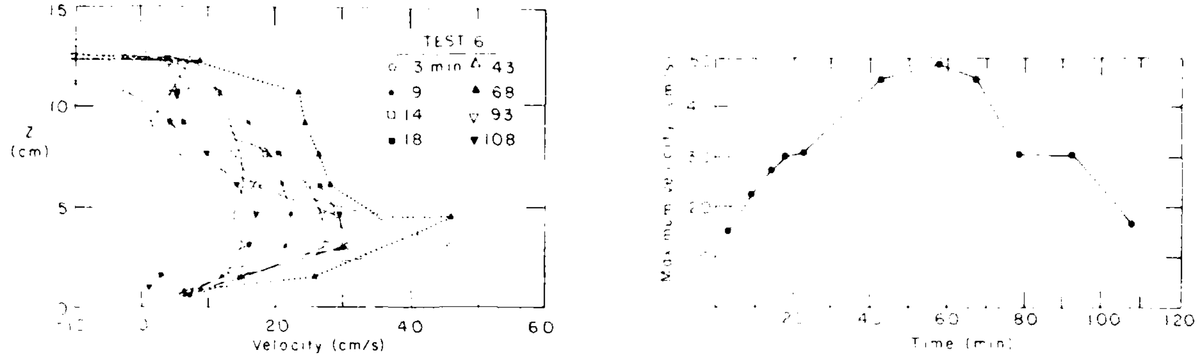


Figure 5. Freezeup process of a full-height screen. Water surface elevations exaggerated.



a. Velocity profiles downstream from an expanded metal screen blocked by frazil ice (z = depth).

b. Maximum measured downstream velocity vs time.

Figure 6. Velocities measured at the centerline of the flume in test RF6.

DISCUSSION

The partial impermeable blocking of the frazil ice screen resulted in an increase in maximum downstream velocity with increasing blockage. This is to be expected in an orifice flow regime, where velocity v is related to the difference between upstream and downstream water surface elevations Δh

$$v = C\sqrt{2g\Delta h}$$

where C is the discharge coefficient, usually about 0.6, and g is the acceleration due to gravity. It was not clear from these tests whether the velocities in the lower, unblocked portion of a prototype structure would be high enough to prevent complete blocking by frazil ice. If this were so, the region of increased velocity near the streambed would be expected to occur throughout the period of partial blocking, which could be several months.

The initial blocking of the test structure by frazil ice resulted in freezeup, and the blockage proceeded from the water surface downwards, similar to the process previously modeled using the impermeable barriers. We observed the same type of flow regime, characterized by an increase in maximum downstream velocity with time. Unlike the earlier tests, however, the blockage created by actual frazil ice was a permeable barrier of irregular shape that changed with time. Piping through the porous mass was evident, resulting in the formation of velocity jets. As a result, the velocity profiles measured at the centerline of the flume may not be considered representative of the entire width of the flume. Large variations in the velocity across the flume at a given depth were observed in a similar series of tests on various types of trash racks,* an example of which is shown in Figure 7. The profiles obtained may be used, in a qualitative sense only, to indicate the general flow trend. The initial flow regime observed can be analyzed as one of orifice flow,

*Personal communication with A. Andersson, Luleå University, Luleå, Sweden, 1988.

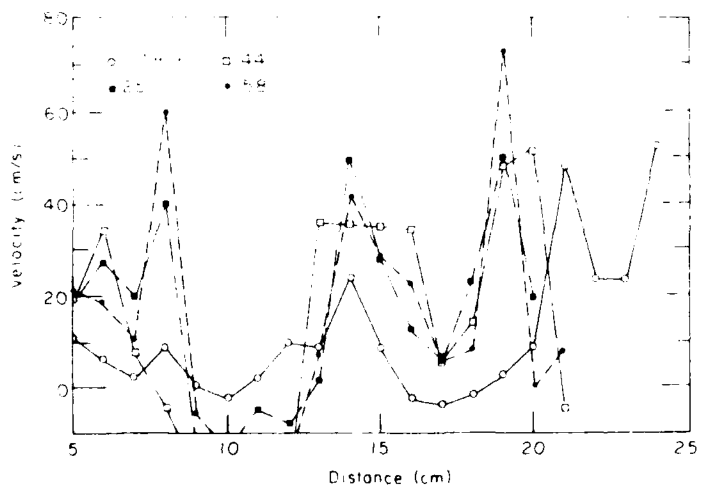


Figure 7. Velocity profiles at mid-depth across the flume about 20 cm downstream from a test structure of 0.95-cm bars spaced 2.54 cm apart (from unpublished data of Andersson).

where velocity is proportional to $\Delta h^{1/2}$. Analysis of the early portions of the tests showed that maximum velocity is proportional to Δh^x, where x varies from 0.16 to 0.55. Again, the irregularity of the frazil ice mass and the piping, combined with measured velocity profiles at only the centerline, make quantitative analysis difficult.

The orifice flow stage is followed by the transition stage, which includes both orifice-type flow and flow through the porous frazil ice deposit. When the screen became completely blocked by frazil ice, flow through the porous ice mass was predominant. Flow during this stage may also be a combination of piping through the frazil ice dam as well as permeable flow. Permeable flow may be described by Darcy's Law

$$v = K \frac{\Delta h}{\ell}$$

where K is the hydraulic conductivity of the porous medium and ℓ is the length of the flow path. Little is known about the hydraulic conductivity or the effects of piping on discharge through frazil ice deposits. However, analysis of the later test stages indicated that a linear relationship between v and Δh was achieved in some cases, indicating that laminar permeable flow may indeed occur.

Weir flow over a solidified frazil ice dam has been observed in the field and is expected in the tertiary phase of freezeup. The upstream ice cover that developed in all tests using frazil ice was a combination of shore ice growth from the sides of the flume and hydraulic thickening of the ice cover that initiated at the screen. Ice booms placed upstream from dams form the same type of ice cover that we observed in the flume, but there is generally open water between the dam and the boom, allowing weir flow over the dam. Some weir flow was seen during the tests, but the frazil ice dam did not solidify to any degree. The lack of a boom and the presence of the ice cover at the structure hindered weir flow over the porous ice dam, perhaps prolonging the period of permeable flow. Discharge in a weir flow regime is proportional to $bH^{3/2}$ where H is the water surface elevation above the top of the weir and b is the width of the weir. The weir flow observed in these tests was accompanied by sufficient discharge through the frazil ice dam that this relationship would be difficult to ascertain.

The data obtained and the observations made during the tests show that frazil ice accumulation is a very complex process. This complexity precluded quantitative analysis. The blocking stages described above, which were determined qualitatively, are shown in Figure 8.

The rate of progression of freezeup in the second set of tests that used frazil ice was seen to be a function of seeding rate for the given cooling rate and turbulence.

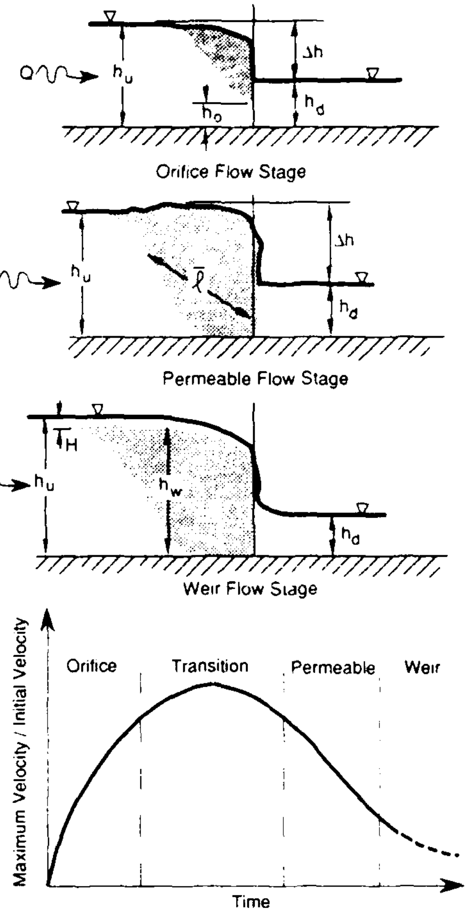


Figure 8. Stages of flow during blocking of a frazil ice screen. Orifice flow characterizes a partially blocked screen and permeable flow, a completely blocked screen.

The higher seeding rate obtained using the seeder led to a more rapid freezeup of the test structure. The three mechanisms of freezeup observed were frazil ice adhesion to both the structure and to accumulated frazil ice, thermal ice growth and mechanical blocking. Mechanical blocking of the screen by entrained flocs and underturning ice was the major process contributing to freezeup during the tests. As was observed in the experiments, active frazil adheres quickly to foreign objects in the water and grows rapidly (Michel et al. 1984, Perham 1981). Passive frazil reportedly has less tendency to adhere to objects, so that frazil ice accretion and adhesion may play less important roles in the blocking process in areas of passive frazil. Further work should be done using passive frazil so that we can identify differences in blocking rates. A screen that blocked rapidly had a shorter period of increased downstream velocity than one in which blocking occurred slowly. Since bed scour can take place during the time of increased velocity, a rapidly blocked screen should cause less scour than a screen that blocks slowly or incompletely

SUMMARY

A set of experiments designed to measure the blocking dynamics of a frazil ice screen was conducted. These experiments showed that partial impermeable blocking of the upper portion of an expanded metal screen resulted in a region of high velocity near the bed. A second series of tests used actual frazil ice produced in a refrigerated hydraulic flume to test partial and complete permeable blocking of the test structure. The frazil ice accumulation process was seen to be a complex one, resulting in qualitative analysis. Velocity profiles measured in the tests indicated three phases of blocking—the orifice flow stage, a transition stage and the permeable flow stage. The transition and permeable flow stages included piping through the porous frazil ice dam. A fourth phase—weir flow—was observed in some tests and is expected to occur in prototype structures.

The results of the present tests indicate that a completely blocked frazil ice collector, characterized by permeable flow or weir flow, is desirable to minimize the time in which bed scour occurs. Speed of blocking is related to the time in which orifice flow, and possible bed scour, will occur. The location of the screen structure in an area of high frazil production, with active frazil, will be important in obtaining a successful, rapidly blocked, screen-type frazil ice collector.

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13. ABSTRACT (*Maximum 200 words*)

Fence booms made of wire mesh screen have been proposed as economical, temporary frazil ice control structures. These screens incorporate frazil ice as it freezes to the screen material, eventually forming a frazil ice dam and raising the water level at a specified location. The purpose of raising the water level is to allow the formation of a stable ice cover that will incorporate still more frazil ice through hydraulic thickening of the cover and deposition beneath the cover. A series of experiments examining the freezeup and blocking dynamics of an expanded metal frazil ice screen were conducted using both an impermeable barrier and frazil ice. A qualitative analysis of the complex frazil ice accumulation process indicated three phases of blocking—an orifice flow stage, a transition stage, and a permeable flow stage. A fourth phase, weir flow, was observed in some cases, and is expected to occur in prototype structures. High downstream flow velocities were associated with the orifice and transition stages. Downstream velocities decreased during the permeable flow stage, although piping resulted in velocity jets. The test results indicate that a rapidly and completely blocked screen is desirable to minimize the time during which high downstream velocities, which lead to bed scour, occur.

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